PROCEEDINGS, Thirty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30-February 1, 2006
SGP-TR-179

EXPLORATION AND TARGETING OF THE SOCORRO, NEW MEXICO DIRECT USE GEOTHERMAL EXPLORATION WELL, A GRED III PROJECT

Richard M. Baars[1], Lara Owens[1], Harold Tobin[1], David Norman[1], William Cumming[2], Greg Hill[3]

[1]New Mexico Tech
801 Leroy Place
Socorro, New Mexico, 87801, USA
e-mail: RMBaars@nmt.edu
Lara@nmt.edu

[2]Cumming Geoscience
4728 Shade Tree Lane
Santa Rosa, CA 95405
e-mail: wcumming@wcumming.com

[3]Consulting Geologist
785 Andrew Lane
Reno, Nevada 89521 USA
e-mail: hillgreg@charter.net

ABSTRACT

The Socorro Peak uplift in central New Mexico is the center of a local zone of high heat flow indicated by shallow thermal gradient wells that encountered heat flow as high as 490 mW/m^2 and measured temperatures of 43°C at 60 m depth. Aqueous geochemistry and mixing relationships in warm springs (32°C) suggest that high Cl fluids at depth have temperatures of over 92°C. A variety of geochemical and geophysical studies, particularly magnetotelluric soundings and soil geochemistry profiling, have identified a drilling location in the Rio Grande basin about 1300 m east of Socorro Peak to target a >60°C geothermal reservoir at <1000 m depth. The exploration hole will be drilled in 2006 to determine if geothermal reservoir with sufficient temperature and capacity to provide direct use heating for the New Mexico Tech campus.

High-resolution magnetotelluric traverses, conducted at a 100 m station spacing, were employed to characterize the distribution of resistivity across the range bounding fault on the east side of the Socorro Peak uplift. One and two dimensional inversions of the data show a steeply dipping range-bounding fault juxtaposing resistive footwall Precambrian and Paleozoic rocks and Tertiary volcaniclastics against conductive hanging wall fanglomerates. Within the hangingwall block, the MT profile data identify a 400 m thick aquitard that separates shallow aquifers from deeper target thermal waters.

Selective extraction geochemistry and pH analyses were performed on soil samples collected at 50-100 m intervals along transects paralleling the geophysical surveys in the geothermal resource area. Patterns of volatile trace elements, including V, As, Br, Se and Mo, were typical of those observed over the top of epithermal mineral deposits just east of the area with highest heatflow near Socorro Peak. Rare earth elements exhibit apical anomalies paralleling the major projected range-bounding fault. Soil pH analyses indicate H+ accumulation within the range front (pH 5.5-6.5) compared to background levels (~9.3) observed with the basin, supports a strong presence of geothermal fluids within the mountain block due to secondary permeability. pH signatures correspond well with certain selective extraction detected elements also derived from oxidation cell geochemistry, namely ore-forming metals such as Zn and Cu. These geochemical surveys indicates a focused thermal source at approximately 500-1000 m depth to the east of the range bounding fault with fluid leakage along a highly-fractured range-front fault system.

We chose the drilling target based on a synthesis of thermal gradient data, the geophysical and geochemical information, geologic structure, hydrologic models, and economic factors. The slimhole well will be on the eastern side of the Socorro Canyon fault near the area of highest measured heat flow, and near the intersection of the

Socorro caldera fracture system, a transverse shear zone, and the Rio Grande rift bounding fault, and close to the New Mexico Tech campus. Fluid leakage up or across the range front fault system is a likely host for deep >60°C thermal waters. The borehole will penetrate both the faulted structural conduit as well as permeable sediments below the aquitard within the hanging wall block to evaluate multiple hypotheses for the source of the heat flow anomaly.

INTRODUCTION

The Socorro, New Mexico area has long been known to host a local high heat flow zone. To mitigate rising heating costs, New Mexico Tech initiated a new exploration program in 2004 for a moderate temperature geothermal system that could be developed for direct use heating of its campus. An initial analysis suggested that a >60°C geothermal fluid produced at a moderate flow rate of 300 gallons per minute would be adequate to support a heat exchange system for the existing campus hot water loop.

The scope of the exploration phase for the project has included geochemical and geophysical analyses, culminating with a planned 1000 m exploration hole to confirm the geothermal potential. The geochemical exploration consists of selective ion extraction and pH analyses of 300+ soil samples. The geophysical investigation consisted primarily of a high resolution magnetotelluric survey as well as reanalysis of older geophysical data including gravity, magnetics and temperature gradient hole data.

The campus of New Mexico Tech is located in Socorro, New Mexico, situated within the Rio Grande Rift (Fig.. 1). The backdrop of Socorro's skyline is a large horst block of the rift system called Socorro Peak. The Socorro Canyon fault is a north trending dip slip normal fault along which the largest displacements are observed between the horst block to the west and the basin to the east. The geology of the area is complex. A buried caldera rim bisects the area, with the highest measured temperatures on the high side of the rim, to the north. A regional shear zone called the Morenci Lineament and the basin bounding Socorro Canyon Fault intersect the caldera rim at this prospect near the center of the Rio Grande Rift system (Chapin et al., 1979; Chamberlain, 1999; Witcher, 1988).

The hydrologic model for this area is equally complex. Several published models have been developed based on the temperature and flow from the Socorro warm springs, each containing similar concepts of recharge in the Magdalena Mountains to the west with waters traveling deep into the subsurface, being heated, and forced to flow up dip through the Socorro Peak mountain block by confining geologic layers (Mailloux, 1999, Barroll and Reiter, 1990). Through the 1960's, 70's, and 1980's, a series of 48 temperature gradient wells were drilled to support a earlier geothermal exploration efforts, providing the basis for defining the local geothermal area and identifying the general target zone in which further exploration methods were applied (Barroll and Reiter, 1990).

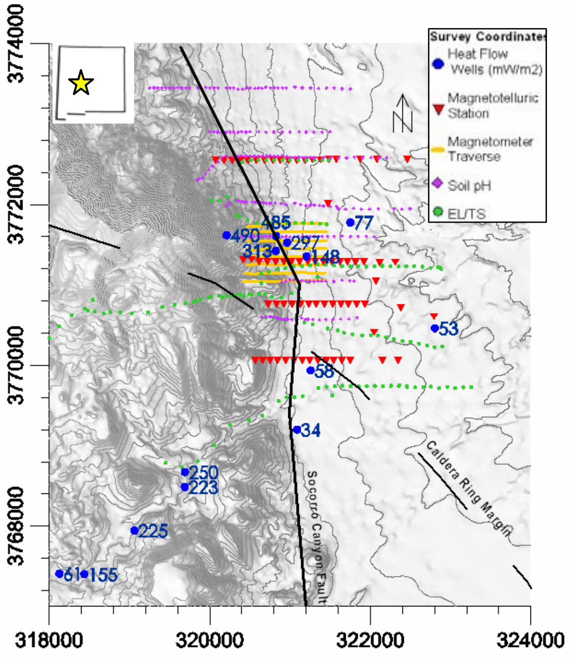

Figure. 1. Topographic map of Socorro Peak with locations of exploration survey stations. Coordinates are in UTM NAD27datum.

GEOPHYSICAL EXPLORATION

Magnetotellurics Survey

In July of 2005 Quantec Geosciences conducted a high-resolution magnetotelluric (MT) survey using their Titan-24 system and standalone MT recorders. The survey was designed to collect data along four MT lines, spaced along the mountain front perpendicular to the strike of the Socorro Canyon Fault, extended from the base of the Socorro Peak mountain block 1.5 km eastward out into the basin. Each MT line contained 15 recording stations spaced 100 meters apart (Fig. 1). The lines were extended with the use of the stand-alone MT recording stations in order to lengthen the MT line as well as fill in data gaps between MT lines. The MT survey was designed to image the structure of the Socorro Peak foothills, the dip and location of the Socorro Canyon fault, the hydrologic stratigraphy of the downthrown block, the rift basin stratigraphy and any subsurface alteration associated with geothermal processes. The MT data quality was high except for some stations closer to the town of Socorro which were distorted by noise.

MT Inversion

Using WinGLink® software, 1D and 2D resistivity processing was used to prepare five cross sections. Four E-W trending cross sections were generated along the MT data with an additional N-S trending cross section parallel to strike (Fig. 2). The stitched Occam 1D inversions of the invariantmode MT data and the 2D inversions showed similar results in the upper 1500 meters (Fig. 3). For 2D inversions, we initially assumed that the Titan-24 profiles were ideal dip profiles and the MT data were rotated numerically to the profile direction to produce 2D inversions (Fig. 4). Subsequent 2D inversions were also based on TE and TM mode decompositions but all of the imaging was similar in the depths of drilling interest. Topography has not yet been integrated into the inversions but is planned.

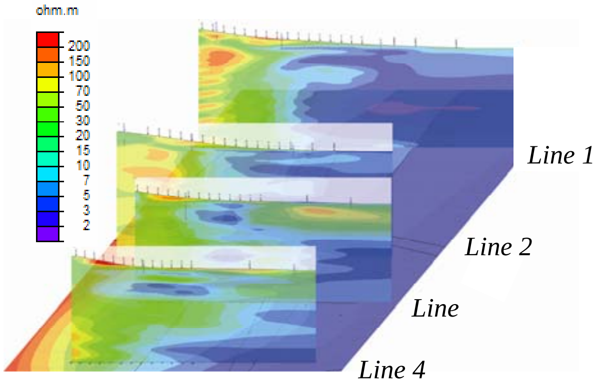

Figure. 2. 1D resistivity fence diagram with resistivity values ranging from 2-200 ohm-meters with cool colors representing low resistivity and warm colors representing high resistivity. Line 1 to line 4 respectively from north to south.

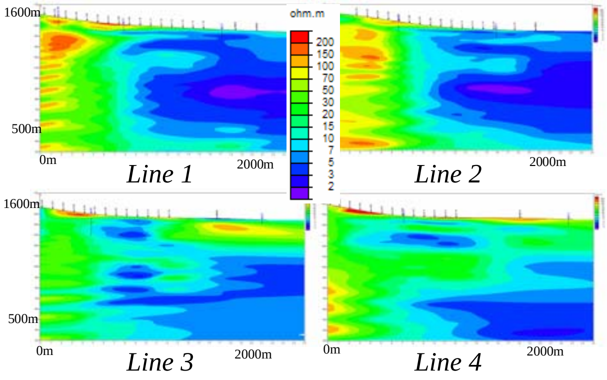

Figure. 3. 1D resistivity cross-sections developed with WinGLink software. Resistivity values range from 2-200 ohm-meters with cool colors representing low resistivity and warm colors representing high resistivity.

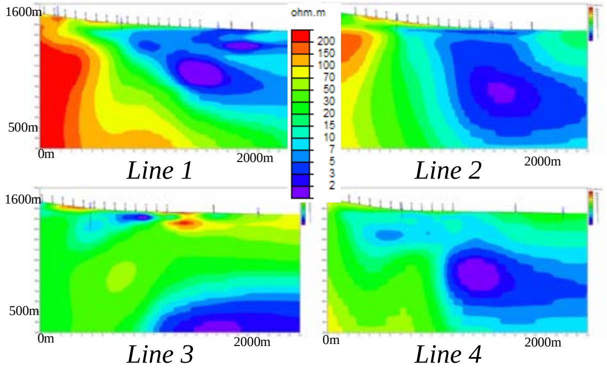

Figure. 4. 2D resistivity cross-sections developed with WinGLink software. Resistivity values range from 2-200 ohm-meters with cool colors representing low resistivity and warm colors representing high resistivity.

MT Interpretation

The profile resistivity range from 1 ohm-m (blue) to 200 ohm-m (red). Resistivity of 1 to 15 ohm-m (blue to light blue) is correlated the Popotosa and similar clay-rich zones or, possibly, warm aquifers, on the east end of the profiles. The 20 to 200 ohm-m (green to red) zone is correlated with the porous altered volcanics and crystalline rocks in the mountain block on the western end of the profiles. Between these and in the basin there is a zone of intermediate 5-15 ohm-m (light blue to green) resistivity that probably consists of course alluvial material. These resistivity patterns correlate closely with the current geologic model of the region.

Although the geology of the sub-basin is poorly constrained, the deepest well in the area reached a depth of only 310 meters, just penetrating the upper contact of the upper Popotosa clay playa aquitard, the largest confining layer in the region. This clay unit is correlated with the 300-400 m thick low resistivity unit with a top imaged at about 300 m depth in profiles 1, 2, 3, and 4 (Fig. 3). No buried bedrock blocks are imaged in upper 1500m of the basin east of Socorro Canyon fault trace.

The Socorro Canyon fault that bounds the western edge of the basin in all the sections is interpreted to lie within the intermediate resistivity transition zone of conductive down-faulted coarse alluvium between the resistive mountain block and the conductive basin (Fig. 2). Large fanglomerate facies formed during periods of rapid uplift have been mapped to the north and south of this area (Chamberlain, 1999).

Although the strongest contrast in resistivity is between the mountain block on the west and the basin on the east, there is also a significant gradient in resistivity from north to south. The volcanics below 700+ m depth on the west end of Lines 3 and 4 are lower in resistivity, 15 to 70 ohm-m (green to yellow), than the 70 to 200 ohm-m (yellow to red) crystalline intrusives in Lines 1 and 2. These patterns are consistent with the caldera rim between Lines 3 and 4 that elevates the resistive mountain block to the north. The north to south resistivity patterns in the basin are consistent with the expected thinning of the Upper Popotosa clay playa from north to south (Chamberlain, 1999).

Magnetic survey

A magnetic field survey was conducted with a Geometrics 858 cesium magnetometer over the localized heat flow area in an attempt to map any near-surface expression of the Socorro Canyon fault. The survey was conducted along a series of eight lines spaced 100 m apart oriented E-W perpendicular to the strike of the Socorro Canyon fault (Fig. 1). The data was drift corrected to a local base station and surveyed by WAAS GPS. The data was also corrected for artifacts and smoothed (or upwardly continued). The data set showed little or no evidence or potential correlation the Socorro Canyon fault. The thickness of the surface alluvium over the magnetic rocks is probably the dominant control on ground magnetic patterns in this area.

Gravity Survey

Gravity data was collected in the 1970's and 1980's by Sanford et al (1968). The 654 gravity stations were reanalyzed using WinGLink software. Preliminary work has included a standard Bouguer anomaly map and a cross section modeled with results consistent with current geologic cross sections of the area. The cross section was modeled from data closest to MT Line 2. The results of this gravity survey support the expected lithologic properties and dimensions of the sedimentary basin. Further work with the gravity data needs to be conducted over MT Line1 1, 3, and 4. (Sanford, et al, 1968).

GEOCHEMICAL EXPLORATION

Selective Extraction Geochemical Analyses

Selective extraction geochemical analyses were performed within the field study area in an attempt at to create a 2D surficial profile of the geothermal system. 190 soil samples were collected from the B-horizon at 100 m spacing in 5 E-W trending lines, each transecting the range bounding fault and the alluvial basin (Fig. 1). The 25g samples, strained to 18mesh, were prepared with Enzyme Leach™ (EL) and Terrasol ™ (TS) agents by Actlabs in Tucson, AZ and analyzed for trace element contents using ICP-MS. Hill et al. (*this issue*) has a detailed discussion of EL and TS. In general TS is the less sensitive technique used for shallow ore, geothermal, and hydrocarbon systems. EL is best to detect deeper systems.

Most of the trace elements in this study detected by TS and EL analyses indicate anomalous concentrations of a magnitude or greater within the soil. The EL and TS data produce similar anomalies with the exception of some Rare Earth elements that are highlighted only within the TS analysis suite. Thus, the observations reported here are supported by both methods.

Profiles of the oxide suite elements (I, Br, Th, V) and some commodity suite elements (As, Li, Sr, Ba) illustrate halo shaped anomalies around a common target near the base of the range front (Fig. 5), indicating a reducing source. This particular anomaly is interpreted as a significant indication of a buried geothermal plume trapped well below the surface (Hill et al., *this issue*). A much larger anomaly haloing a central low observed within the basin is reoccurring in many of these same elements, yet is not as well restrained. The size and locale of this second anomaly corresponds with a discontinuity in the conducting unit as imaged by the MT data.

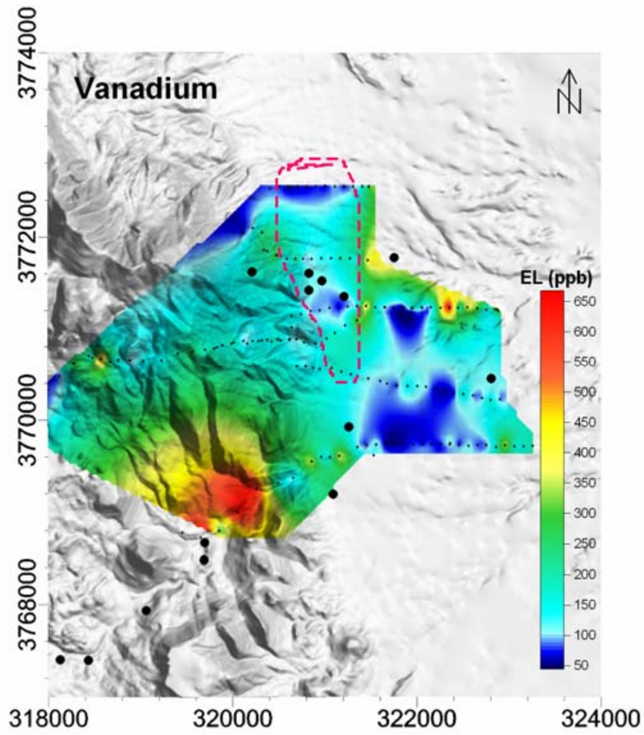

Figure. 5. Vanadium Enzyme Leach concentration profile of halo anomaly outlined in purple. This anomaly is above areas of elevated heat flow as determined by thermal gradient wells (black filled circles).

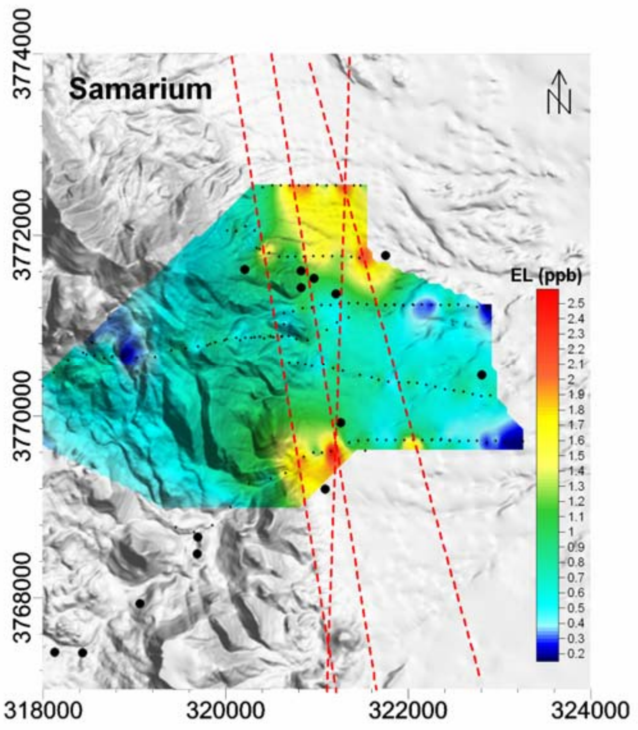

Figure. 6. Samarium Enzyme Leach concentration profile of linear anomalies outlined in red.

Profiles of the rare earth elements (REE) indicate anomalous concentrations paralleling the range front to the west indicating substantial heat and/or fluid penetration through the uplifted fault block (Fig. 6). Though the precise location of the range-bounding fault trace cannot be identified from these surveys, the linear nature and intersecting trends of these multiple anomalies suggest a complicated and densely-fractured structural conduit.

Soil pH Analyses

The analysis of soil pH is a new method being developed in the oil, gas and mineral exploration fields and is being tested here for its feasibility in constraining the location of geothermal fluids. Hydrogen ions along with other oxidized elements are released by redox reactions across electrochemical cells formed at the interface between a reducing environment such as a geothermal body or saturated unit and O_2 rich environment such as unsaturated alluvium (Hamilton, 2004). This project utilizes the soil pH method to supplement selective extraction geochemical exploration and to investigate its validity as a low-cost substitute method for identifying buried structures and fluids within a geothermal system.

Two-hundred and ten soil pH samples were collected along 9 E-W trending transects, roughly overlapping the same target area as the EL and TS survey (Fig. 1). Tighter 30-50 m sample spacing was utilized across the range front in order to better identify fluid movement bounded by secondary permeability, and increased to a 100 m spacing in the basin where the anomalies are thought to be more diffuse. Soil was sampled from the upper 5-10 cm depth in soil profile, with special attention paid to avoid vegetation, organic peat or caliche. If caliche was detected at >10cm depth, soil was collected in the upper 5 cm of the profile and tested for excess acidity. Soil pH analyses were performed on a soil-slurry formed from –18 mesh, 3 cc soil samples mixed with 50 mL reverse osmosis (R.O.) purified water buffered to pH 6.0 and stirred and agitated for a minimum of 2 minutes (Smee, 1999). These analyses were conducted in the lab no more than 2 hours following soil collection to produce high quality results.

Soil pH profiles illustrate an overall trend of anomalous H+ concentrations (pH ~ 6.5) within the range front, decreasing to background values within the alluvial basin (pH ~9.3). The most pronounced anomalies (pH > 6.2) occur largely within the southern half of the field area (Fig. 7) where hill slope topography is the greatest and the trace of the range-bounding fault is best constrained. The pH measurements show a central low that nests mostly within central lows for oxidation suite elements (Fig.. 5) Soil pH anomalies form linear patterns (Fig. 7) similar to those observed in the EL and TS (Samarium) profile, particularly the rare earth elements plots (Fig. 6), high field strength elements and transition metals (Cu, Cd). These patterns, produced by redox chemical cells, support the presence of geothermal fluid in the basin adjacent to the fluid penetration through the fractured mountain block and along the permeating structural conduits, including the range-bounding fault and extending into valley-fill east of the fault block. The pH anomaly we assume is the result of a all leachable ions in the cell. Hill et al. (*this issue*) shows that the diameter and location of the element lows vary from element to element. The pH being a composite of all elements data therefore understandably show a broad and diffuse boundary, and a smaller central minimum than individual element plots

The location of these linear anomalies tends to be offset from element to element. More volatile elements may be transported through the unsaturated overburden more easily than less volatile elements, which are aided to the surface along faults and fractures (Hamilton, 2004). In accordance, linear anomalies indicated by the soil pH analyses (Fig. 7) are observed within the fractured mountain block, while the same linear anomalies observed within the REE selective extraction suite (Fig. 6) are observed further to the east (Hill et al., *this issue*). This observation indicates that the conductivity differential between the two juxtaposed strata (saturated bedrock and Oligocene volcanics against unsaturated, oxygen-rich flanglomerates) may act as an oxidation cell, thus producing a source of H+ and free ion volatilation.

The reproducibility of the soil pH and selective extraction geochemical analyses attests to the usefulness of pH surveys as a low-cost, high yield method for identifying geothermal fluids associated with redox chemical cells formed along structural conduits. We believe this method is a good 1st order approach to geothermal resource exploration in a Basin & Range-type system.

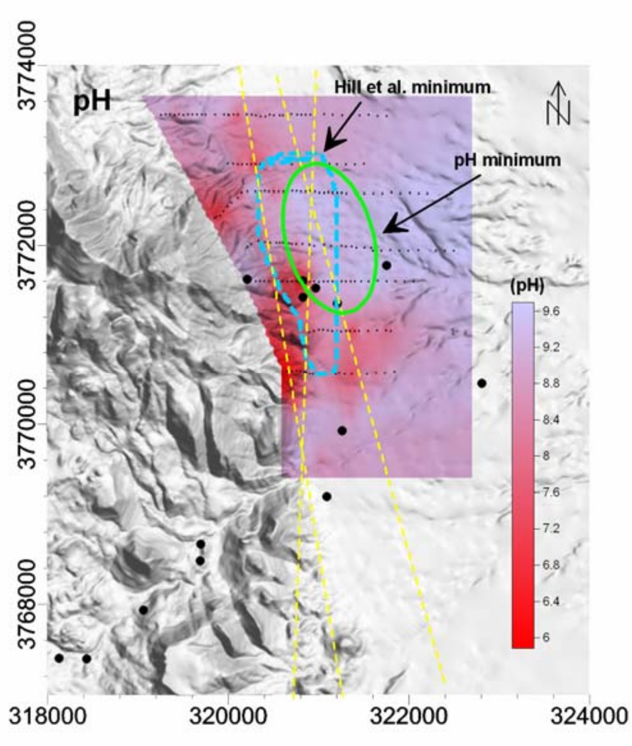

Figure. 7. Soil pH profile showing central low in green. Yellow dashed lines indicate linear anomalies. Anomaly observed in oxidation suite EL surveys (Hill et al) outlined in dashed blue line.

CONCEPTUAL MODEL

A conceptual analysis of the Socorro Peak geothermal system has been developed based on available heat flow, hydrologic and geologic models and the new geophysical and geochemical data. Like other Basin and Range style systems, the Rio Grande rift has created an asymmetrical tilt and uplift of a basement fault block with adjacent half grabens, such that fluid in the recharge area of the Magdalena Mountains can travel deep into the basin subsurface eventually getting trapped under thick Upper Popotosa aquitard materials. The fluids are then heated and travel through the Socorro Peak mountain block along fracture and matrix permeability. These heated fluids are manifested as mixed warms springs flowing from the uplifted fractured volcaniclastics to the south of the target area; however, it is speculated that deeper and presumably higher temperature advective fluids are flowing into a confined aquifer within the downthrown block capped by Popotosa playa sediments. The presence of geochemical anomalies and an elevated geothermal gradient focused along the range-front supports this transportation model and indicates leakage of geothermal fluids along Socorro Peak faults. A conductive unit observed in most of the MT profiles and surficial geochemical anomalies above this unit support the presence of a deep thermal aquifer within the graben block fed by the fractured footwall bedrock (Fig. 8).

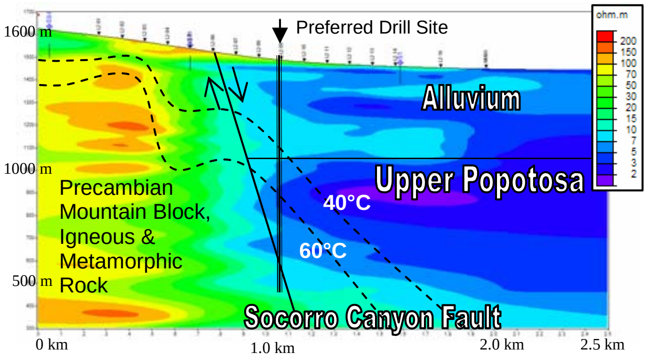

Figure. 8. MT line 2 1D inversion, with Socorro Canyon Fault and proposed drill target. Resistivity contoured from 2-200 ohm-meters. Cool colors represent low resistivity and warm colors represent high resistivity

Drilling Target

The exploration drill hole is sited to provide optimal knowledge of the subsurface structure and hydrologic system. The 1000m slimhole well is aimed at intersecting the Socorro Canyon fault at approximately 800 m in an attempt to characterize both the geothermal aquifer within the hanging wall and the fractured bedrock within the footwall (Fig. 8). The hole is sited far enough in the basin that it will penetrate the upper 300 m of Quaternary alluvium, the Upper Popotosa clay playa aquitard and finally the brittle silicified conglomerate of the Lower Popotosa before intercepting the Socorro Canyon Fault. Chip and core logging will provide some stratigraphic information, particularly focused on the Lower Popotosa conglomerates and underlying Tertiary volcanics believed to host the geothermal aquifer. Geophysical slimwell logging and pumping tests will characterize the quality of the geothermal aquifers as a whole. Currently it is speculated that the source of advection is the granitic mountain block heated by deep circulating thermal fluids. Penetrating into the fractured bedrock by crossing the fault will test this flow regime.

The area below Woods Tunnel (Fig. 9) has been chosen as a surface drill location to integrate the elevated heat flow data and is backed with the confidence in the geologic cross section as well as the MT profile at depth. In close proximity to maximal heat flow along the fault, our target location still retains values of ~148 mW/m^2, though dampened by the cooler shallow Rio Grande fluvial aquifer (Fig. 8). The target is situated along MT line 2, clearly illustrating a conductive unit at approximately 660m depth. This MT cross section appears to correlate with drill log data and lithology in the area and provides a reasonable approximation of what should be expected at depth. Halo shaped SILG anomalies centered around our target also indicate a deeper geothermal reducing body in concurrence with interpretations by Hill et al (*this issue*).

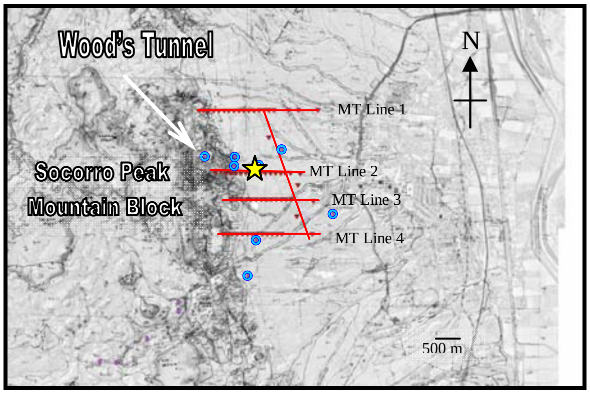

Figure. 9. Drill target marked with yellow star. MT lines marked in red lines with thermal gradient wells marked with blue circles. Wood's tunnel well is marked with arrow and has the highest heat flow values of 490mW/m^2 .

CONCLUSION

The exploration of a geothermal system in Socorro, NM has utilized both geochemical and geophysical techniques resulting in favorable prospects for accessing a low-to-mid temperature reserve. The proposed drilling location is consistent with all available data and provides the best prospect for characterizing the geologic and hydrologic structure of the system while testing the economic potential of the resource. A magnetotelluric survey proved a very useful tool in this study, particularly by identifying the location of a targeted conductive aquifer below the basin. Geochemical results are consistent with the existence of this aquifer and the conceptual hydrothermal model to be tested in the next phase.

FUTURE WORK

The possibility of a seismic refraction survey to image the subsurface as well as the Socorro Canyon fault is being analyzed for feasibility and ability to image the subsurface in a cost effective manner.

Drilling the exploration hole and the associated downhole testing will be the most valuable part of this project. Currently the drilling is in the design and bidding process. The drilling will provide final data for the extent of this phase of the project. A series of downhole geophysical logs will be collected as well as standard hydrologic tests to determine the geothermal potential. Pending successful results further analysis will be conducted on the likely resource sustainability, the design of production and injection wells, and the design of the direct use system.

ACKNOWLEDGEMENTS

Funding for the work presented is from DOE GRED III grant DE-FC36-04GO14342, Geothermal Energy for New Mexico Tech: Assessment of Potential and Exploratory Drilling. We would also like to thank professional consultant Jim Witcher for his expertise and dedicated assistance. We thank Sandia National Labs for advice and support with drilling logistics. We also thank the Energetic Materials Research and Testing Center (EMRTC) at New Mexico Tech for their cooperation during this study.

REFERENCES

Barroll, M.W. and Reiter,M. (1990), "Analysis of the Socorro hydrogeothermal system: Central New Mexico," *J. Geophys. Res*., **95**, 21,949-21,963.

Chamberlin, R.M. (1999), "Preliminary geologic map of the Socorro quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources", Open-file Digital Map Series OF-DM-34, 46p. (scale 1:24,000)

Chapin, C.E., Sanford A.R., White, D.W., Chamberlin, R.M., Osburn G.R., (1979), "Geologic Investigation of the Socorro Geothermal Area", N.M. Bur. Mines and Miner. Resour. Report NMERDI 2-65-2301.

Hamilton, S.M., Cameron, E.M., McClenaghan, M.B., and Hall, G.E.M., 2004, Redox, pH and SP variation over mineralization in thick glacial overburden. Part I: methodologies and field investigation at the Marsh Zone gold property, *Geochem.: Explor., Environ., Anal.*, **4**, no.1, 33-44.

Hill, G., Norman, D.I., L. Owens, L.B.. (2006),"Surface Geochemistry in Exploration for a Buried Geothermal System, Socorro, New Mexico". *Proceedings 31st Workshop on Geothermal Reservoir Engineering, Standford University, these proceedings*.

Mailloux, B., Person, M, Kelley, S., Dunbar, N., Cather, S., Strayer, L., and Hudleston, P., (1999), "Tectonic controls on the hydrogeology of the Rio Grande Rift, New Mexico", *Water Resources Research*, **35**, 2641-2659.

Sanford, A.R., (1968),"Gravity Survey in Central Socorro County, New Mexico"., SBMMR Circlular 91.

Smee, B.W., (1999), "The effect of soil composition on weak leach solution pH: a potential exploration tool in arid environments". *Explore*, **102**, 4-7.

Witcher, J.C., (1988), "Geothermal resources of southwestern New Mexico and southeastern Arizona", *Field Conf. Guideb. N.M. ~1. Soc*., **39**, 191-197.